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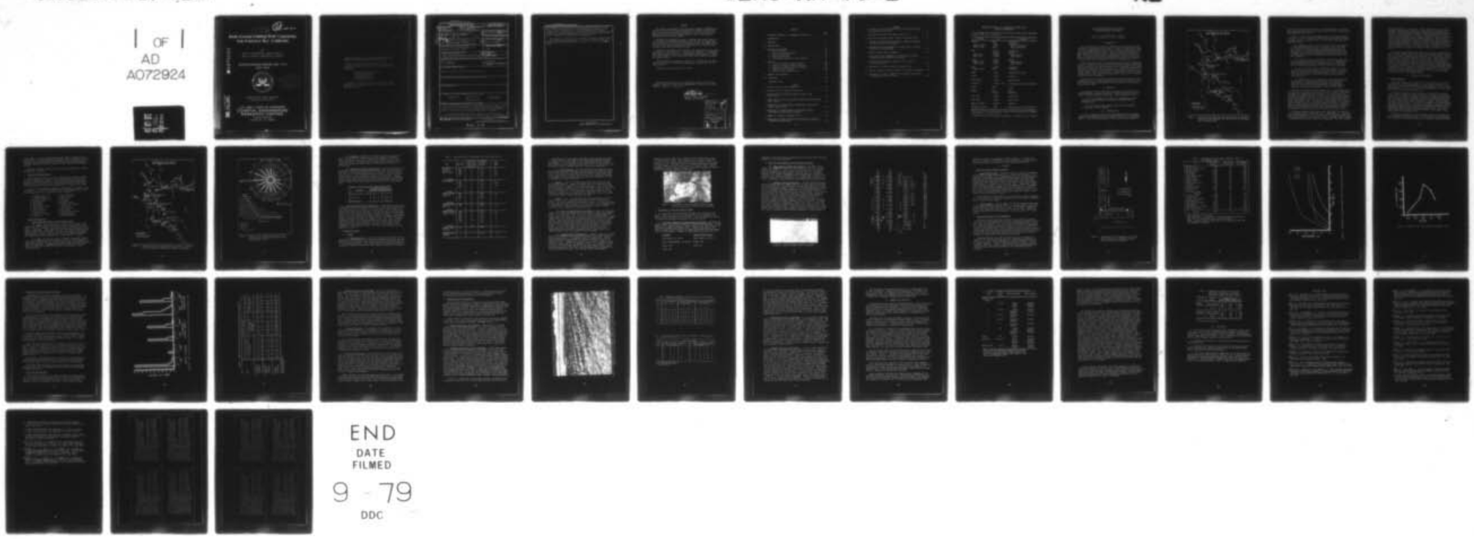

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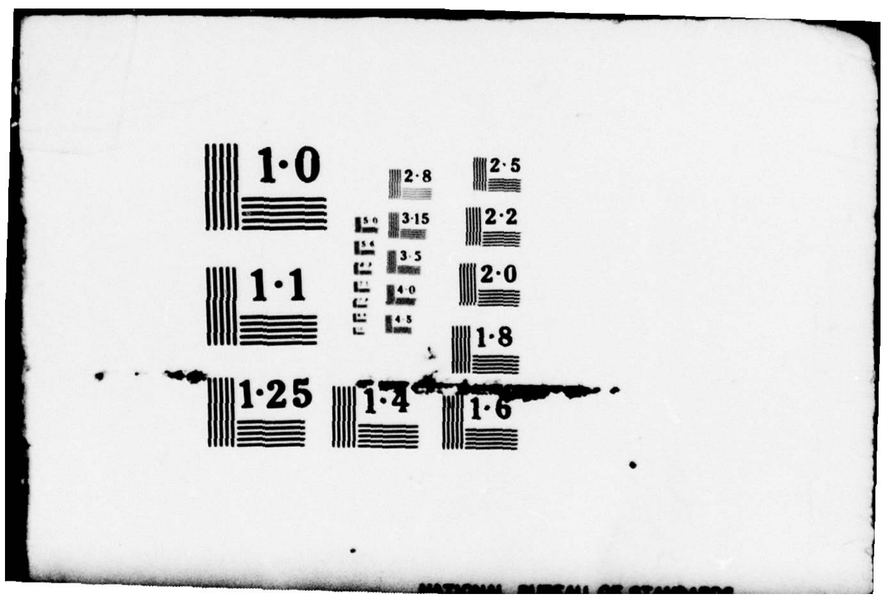
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Bank Erosion Control With Vegetation, San Francisco Bay, California

by

Curtis L. Newcombe, James H. Morris,
Paul L. Knutson, and Carol S. Gorbics

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During 1975 to 1978, an intertidal shoreline stabilization study was conducted to determine biological means of controlling erosion. California cordgrass (*Spartina foliosa* Trin.) and mussels (*Ischadium demissum* Dillwyn) were used in San Pablo Bay and South San Francisco Bay, California.

The study indicated that establishing cordgrass with seeds is not a practical method for controlling erosion. Cordgrass plugs are more useful —

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CONT

than sprigs while the cordgrass-mussel plugs, termed bioconstructs, are the most tolerant to erosion by waves. The cordgrass-mussel community bioconstructs survived exceptionally well during the 13-month observations at Alameda Creek, a high-energy site. Once established, they are highly resistant to waves, will survive transplanting, and can be established in an area with up to a 7-kilometer fetch without wave-stilling devices.

The biomass of the aerial parts of 23 natural California cordgrass marshes averaged 1,062 grams per square meter. This value is similar to those previously reported for smooth cordgrass (*Spartina alterniflora*) on the Atlantic coast.

PREFACE

This report is published to provide coastal engineers information on the use of intertidal salt marsh vegetation for erosion control on the open shores of the San Francisco Bay System. The work was carried out under the coastal ecology research program of the U.S. Army Coastal Engineering Research Center (CERC).

The report was prepared by Curtis L. Newcombe and James H. Morris of the San Francisco Bay Marine Research Center, and Paul L. Knutson and Carol S. Gorbics of the Coastal Ecology Branch, CERC, under CERC Contract No. DACW72-75-C-0015 and the general supervision of E.J. Pullen, Chief, Coastal Ecology Branch, Research Division.

Thanks are expressed to all individuals who contributed to this study, particularly to J.W. Walmsley, C. Purser, and R. Mueller. J.W. Walmsley had a major responsibility in all field monitoring operations, C. Purser contributed greatly to the report preparation, and R. Mueller performed the biomass studies.

Special thanks are expressed to Professor H.T. Harvey and A.H. Koch, special consultants in Ecology and Engineering, respectively, for valuable counsel.

Comments on this publication are invited.

Approved for publication in accordance with Public Law 166, 79th Congress, approved 31 July 1945 as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

TED E. BISHOP
Colonel, Corps of Engineers
Commander and Director

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CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: $C = (5/9)(F - 32)$.

To obtain Kelvin (K) readings, use formula: $K = (5/9)(F - 32) + 273.15$.

BANK EROSION CONTROL WITH VEGETATION
SAN FRANCISCO BAY, CALIFORNIA

by
Curtis L. Newcombe, James H. Morris,
Paul L. Knutson, and Carol S. Gorbics

I. INTRODUCTION

The San Francisco Bay system is comprised of four large bays interconnected by constricted straits (Fig. 1). Prior to 1850 the bay system consisted of approximately 2,038 square kilometers of open water, tidal flats, and intertidal marshlands. A total of 810 square kilometers of marsh formed the Suisun, San Pablo, Central, and South San Francisco Bays. Since the mid-19th century, approximately 30 percent of the bay system has been either filled or diked-off and drained in land reclamation activities (U.S. Army Engineer District, San Francisco, 1977).

Intertidal marshes have been the primary target of these reclamation projects. Seventy-five percent of the San Pablo Bay marshes and 85 percent of South San Francisco Bay marshes have been appropriated for urban, commercial, industrial, and agricultural uses. The marshy fringe which once protected the shore from erosion has been greatly reduced or eliminated. Today, much of the shoreline is characterized by near-vertical eroding banks, a small band of intertidal marsh, and a nearly continuous system of levees and landfills.

Considering the historical distribution of marsh vegetation on the margins of the bay, planting intertidal plants may be an effective erosion control measure in San Francisco Bay and other bays and estuaries on the Pacific coast.

II. OBJECTIVE

The objective of this study was to determine the feasibility of using intertidal salt marsh vegetation to control erosion on the open shores of the San Francisco Bay system. Specific objectives were:

(a) The development of techniques for propagation, transplantation, and maintenance of plants for shoreline erosion abatement; and

(b) the field testing of plants and planting techniques for shoreline erosion abatement.

III. PREVIOUS WORK

In 1946, a property owner of the Rappahannock River in Virginia graded an eroding bank and planted several varieties of salt-tolerant grasses. This work represents one of the earliest known attempts to

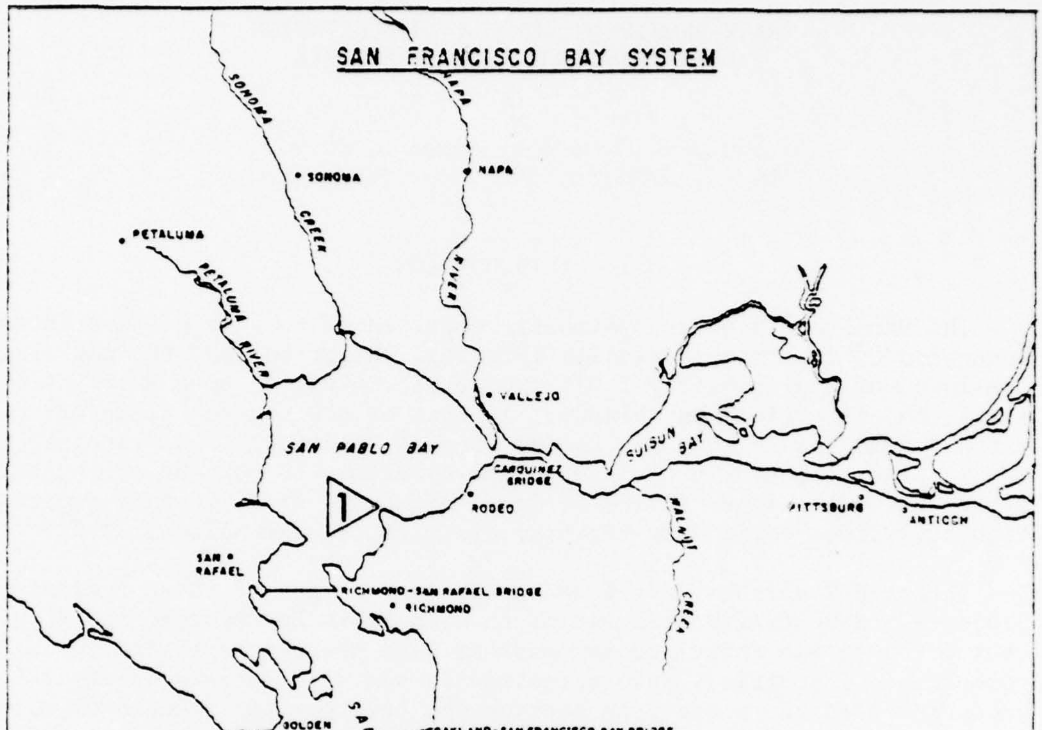

Figure 1. Location of the three shoreline areas in the San Francisco Bay selected for planting: (1) Point Pinole, (2) San Mateo, and (3) Alameda Creek.

abate erosion with intertidal plants in the United States. The planting has prevented erosion for more than 20 years (Phillips and Eastland, 1959; Sharp and Vaden, 1970).

In 1969, the U.S. Army Coastal Engineering Research Center (CERC) initiated, by contract, regional studies on the use of marsh vegetation to control erosion in coastal areas. The following studies have been completed to date:

(a) Woodhouse, Seneca, and Broome (1974, 1976) found smooth or salt marsh cordgrass (*Spartina alterniflora*) to be an effective stabilizer of eroding banks and dredged material areas in North Carolina. Between 1969 and 1976 detailed techniques were developed for the efficient propagation of cordgrass with sprigs and seeds, and the factors which affect growth and survival were well documented.

(b) Garbisch, Woller, and McCallum (1975) found smooth cordgrass and saltmeadow cordgrass (*Spartina patens*) to be effective in controlling erosion in the Chesapeake Bay area. Efficient nursery production techniques for these species were developed.

(c) Hall and Ludwig (1975) evaluated the potential use of vegetation for erosion abatement in the Great Lakes. They found that marsh vegetation had limited potential because of fluctuating lake water levels, high bluffs, winter icing conditions, and severe waves.

(d) Dodd and Webb (1975) and Webb and Dodd (1978) appraised the potential of vegetative stabilization on the gulf coast. They found that smooth cordgrass and gulf coast cordgrass (*Spartina spartinae*) could be established on eroding banks if temporary protection was afforded by a wave-stilling device.

Little prior research has been conducted on the use of marsh vegetation for bank stabilization on the Pacific coast. However, developing techniques for propagating select species of salt marsh plants has received considerable attention in recent years. Most work has focused on California cordgrass (*Spartina foliosa*) which occurs intermittently along the California coast and the coast of Baja California, Mexico (Munz, 1968; Mason, 1969). This grass is most abundant in San Francisco Bay, San Diego County, and in several estuaries in Baja; is sparse or absent in bays and estuaries north of San Francisco; and is closely related to smooth cordgrass which has been used extensively for marsh development and bank stabilization on the gulf and Atlantic coasts.

California cordgrass grows lower in the intertidal zone than any other emergent plant on the Pacific coast. Where found, it is the dominant plant between mean tide level (MTL) and mean high water (MHW) (U.S. Army Engineer District, San Francisco, 1976). Although uniquely adapted to withstand both elevated salinity and submergence, this plant invades

barren substrates in a slow manner. Purer (1942) noted that California cordgrass seedlings were uncommon and speculated that reproduction of the species was principally vegetative rooting from extensive creeping rhizomes of the parent plant. Phleger (1971) questioned whether the species actually produced viable seed as he failed to achieve germination in the laboratory using several standard techniques. However, Mason (1973) located seed-produced stands of cordgrass and achieved germination in laboratory experiments. Techniques were later developed for establishing cordgrass from seed, plugs, and nursery stock under field conditions (Newcombe and Pride, 1975; Knutson, 1975). Sprigs have also been used successfully to produce new stands of cordgrass (Morris, et al., 1978).

The above field plantings were made in areas totally sheltered from wave activity. Before this study, little had been known about the tolerance of California cordgrass to wave activity in exposed areas. Based on observations of smooth cordgrass on the Atlantic coast, Knutson (1977) concluded that seeds are likely to establish only in sheltered areas. Sprigs are more tolerant to wave activity and can be used reliably in fetches (the distance the wind blows over open water in generating waves) up to about 8 kilometers. Plugs or nursery stock work consistently well in fetches up to 16 kilometers. Knutson also reported that plants can be established in areas exceeding these fetch limits if the slope onshore is gradual, shallow depths occur offshore, or if the site faces away from the direction of predominant winds.

IV. METHODS AND PROCEDURES

1. Plant Selection.

Three plant species are predominant in the intertidal zone in San Francisco Bay. California cordgrass is the principal colonizer in the intertidal zone up to the MHW elevation, and pickleweed (*Salicornia spp.*) and saltgrass (*Distichlis spicata*) are the dominant plants in the higher marsh, MHW to the estimated highest tide.

California cordgrass has considerably more potential for erosion control than the other two plants. Cordgrass is found in the intertidal region which is subject to the greatest wave attack and subsequent erosion. It grows in dense, monotypic stands with semirigid, erect stems. This growth forms a mass that dissipates wave energy. Natural stands with 800 or more stems, 0.3 to 1.2 meters in height, may be crowded into each square meter of marsh. The plant is supported by numerous shallow, underground rhizomes and an extensive root system that stabilizes the sediments in which it grows. During the growing season, roots and rhizomes constitute 50 to 60 percent of the plant's total weight (Floyd and Newcombe, 1976; Knutson, 1976).

Pickleweed and saltgrass grow in the high intertidal zone which is not the region of critical erosion. Neither plant has the erosion control attributes of California cordgrass. Pickleweed is poorly anchored

in the soil. Its root system represents only about 20 percent of the total weight of the plant (Floyd and Newcombe, 1976). Saltgrass is often prostrate (lying on the ground) and spreads from above-ground runners (stolons), providing little resistance to waves and only limited benefit to soil.

Based on the above considerations, California cordgrass was selected for planting experiments.

2. Survey of Existing Marshes.

A field survey of over 23 natural cordgrass marshes was made around the bay in November 1976 (Fig. 2). The total number of culms (stems) per meter and the mean height of stems and biomass were measured (four replicates) for each survey site. These data were used to compare the natural marshes and the marshes planted during the course of the study.

Each site was assigned an alphabetic and geographic designation. The following is a listing of the natural marsh areas sampled and the alphabetic designation used to locate the sites in Figure 2:

A. Alameda Creek Flood Control Channel
B. Bay Bridge Toll Plaza
C. Bolinas Lagoon
D. Burlingame
E. China Camp
F. Corte Madera Creek
G. Coyote Point
H. Creekside Park
I. Drakes Estero
J. Golden Gate Fields
K. Limatour
L. Marin Day School
M. Novato Creek
N. Oro Loma
O. Palo Alto
P. Petaluma Creek
Q. Pinole Creek (mouth); two sites
R. Richardson Bay
S. Seal Slough
T. San Francisco Airport
U. Shoreline Drive
V. Southhampton Bay

3. Field Planting Sites.

a. General Physical Features of San Francisco Bay.

(1) Tides. San Francisco Bay is subject to the Pacific coast semidiurnal tidal pattern of two high and two low tides per day (24.8 hours). Unlike the Atlantic coast, the two high tides and two low tides differ in magnitude. Tidal range within the bay generally increases inland from the Golden Gate Bridge. The mean tidal range at the bridge is approximately 1.3 meters; the southern tip of the South San Francisco Bay (approximately 80 kilometers) has a tidal range of 2.7 meters.

(2) Wind. The wind rose shown in Figure 3 represents the general wind environment of the San Francisco Bay area. The strongest average winds blow from the west; south-southeast winds are also strong but occur less frequently. Strongest winds occur during the winter when storms increase wave heights from 0.3 meter to more than 1.0 meter (Pestrong, 1972).

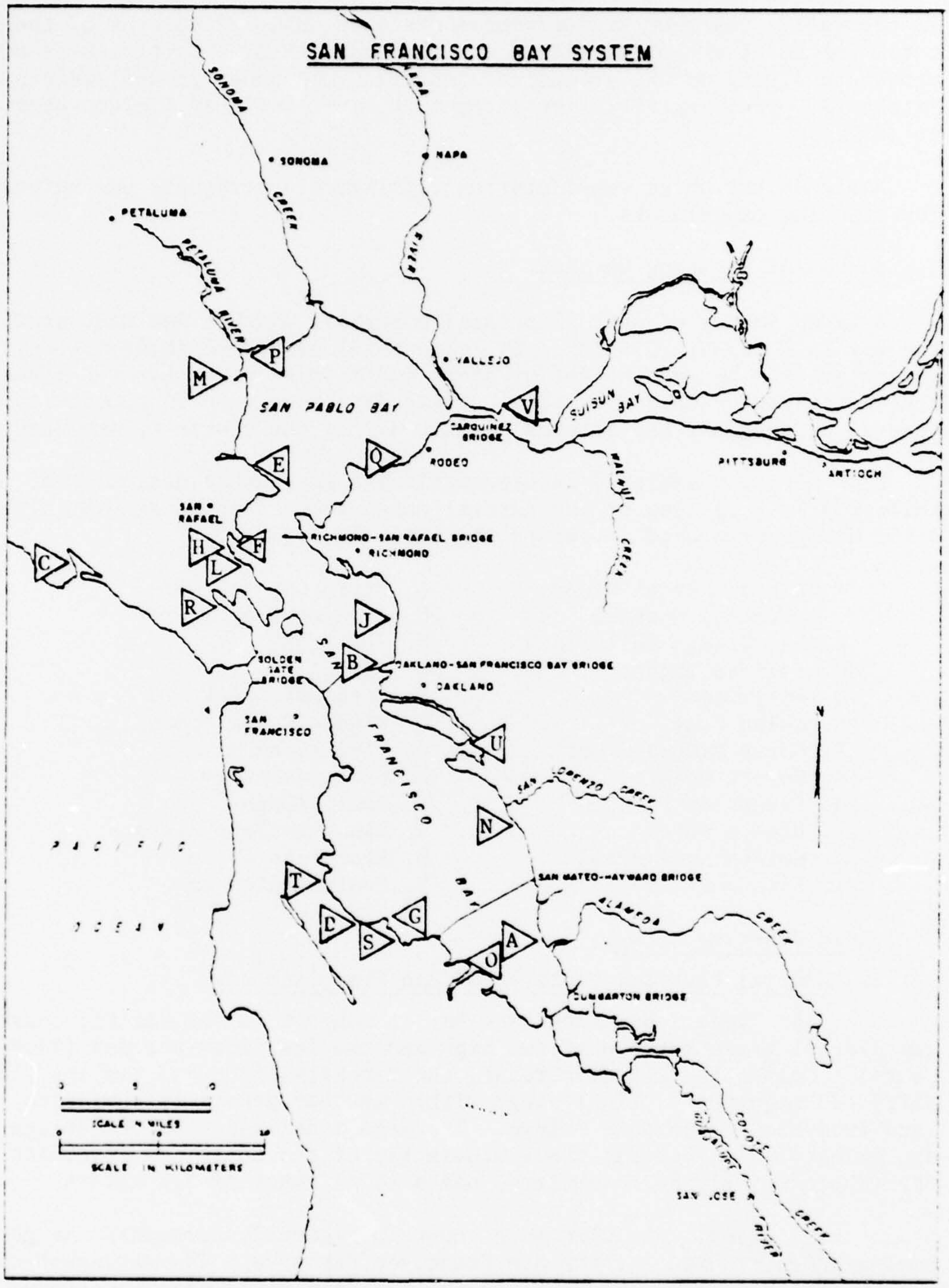

Figure 2. Locations of the 23 natural marsh sites A to V. (Sites I and K 35 kilometers northwest of Golden Gate Bridge.)

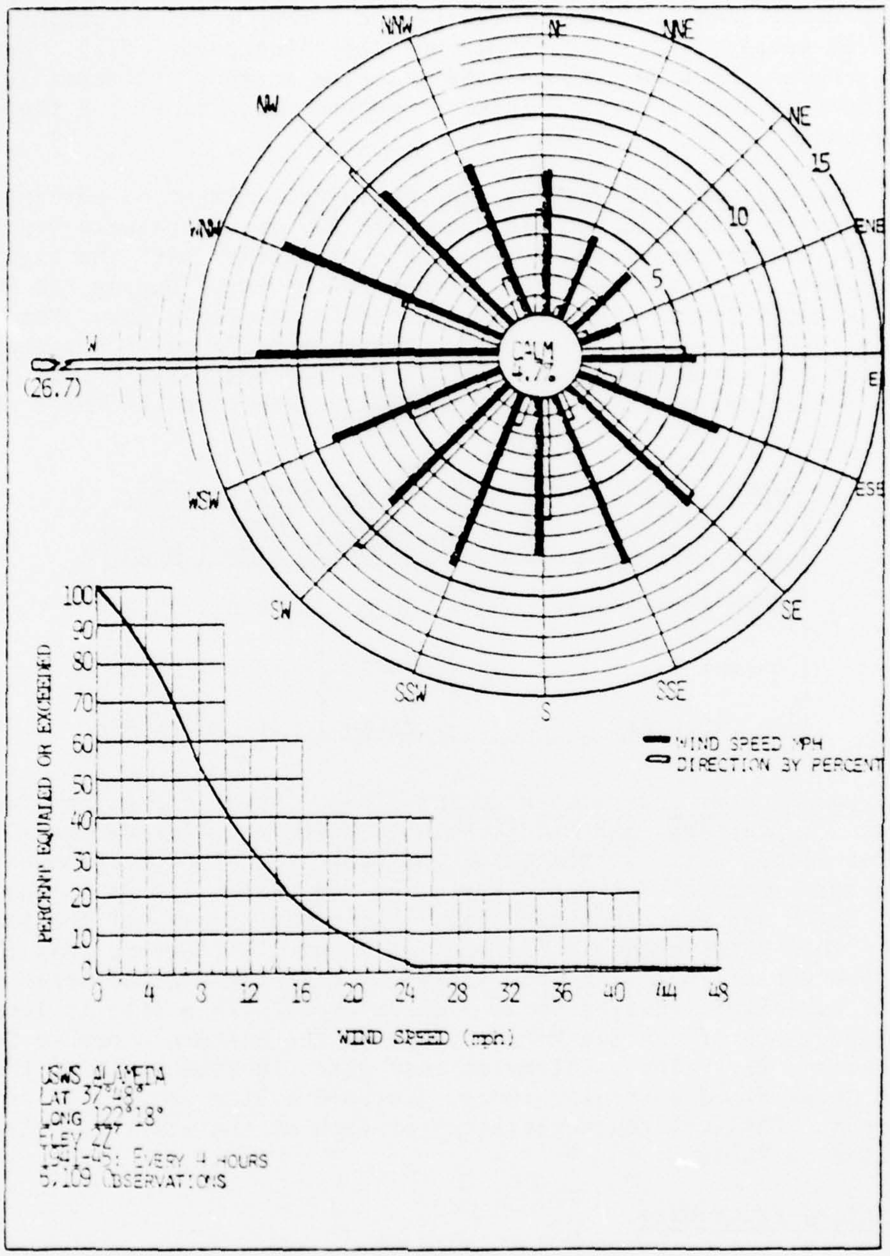

Figure 3. Wind rose for Alameda Island, Central San Francisco Bay (U.S. Army Engineer District, San Francisco, 1978).

(3) Sediments. Sediments on eroding bay shores typically contain 5 percent sand, 15 percent coarse shell fragments and organic debris, 15 percent silt, and 65 percent clay (Pestrong, 1972). Wave action removes the fine-grained material from surface sediments in the swash zone, leaving a surface layer of coarse material at the toe of eroding banks.

(4) Rainfall, Riverflow, and Salinity. Almost 85 percent of the total annual rainfall in the San Francisco Bay occurs between November and April. Major freshwater inflow, which coincides with the high rainfall periods, is in the northern reaches of the bay. During the winter rains, salinity levels are greatly reduced in San Pablo Bay. Maximum salinity levels reach the seawater concentration (33 parts per thousand) during the dry summer months in Central Bay and South San Francisco Bay. Table 1 summarizes mean and extreme salinity levels in the three major bays.

Table 1. Salinity levels in San Francisco Bay.

Location	Salinity level (pct)		
	Maximum	Minimum	Mean
South San Francisco Bay	30.0	18.0	23.7
Central Bay	30.5	18.0	24.5
San Pablo Bay	23.5	1.5	11.5

b. Location of Shoreline Planting Sites. Three shoreline sites were selected for planting--San Mateo, Point Pinole, and Alameda Creek (Fig. 1). The Point Pinole site is located on the east side of Point Pinole on the southeastern shore of San Pablo Bay. The San Mateo site is on the west side of South San Francisco Bay about 3 kilometers north of the San Mateo Bridge. This site extends a distance of about 1 kilometer. Six planting areas were established along the shoreline near the Alameda Creek flood channel, hereafter referred to as Alameda Creek. This site is located 5 kilometers south of the San Mateo Bridge on the eastern shore of South San Francisco Bay. The 1-kilometer test site, located north of the Alameda Creek flood control channel, provided a wide variety of test conditions. Physical characteristics of each of the planting sites are summarized in Table 2.

4. Planting Procedures.

a. Seeding.

(1) Laboratory Tests. Seeds were collected in November 1975 to prepare for field planting. The seeds were harvested by hand at low tide. Inflorescences (seed heads) were clipped from parent plants with the use of electric garden shears. Collected material was threshed and stored in 40 parts per thousand saltwater at room temperature (about 20° Celsius).

Table 2. Characteristics of shoreline test sites (see Fig. 1).

Site	Exposure	Percent of time wind blows from direction	Average windspeed (km/hr)	Fetch (km)
San Mateo,	N.	5	11.3	21
South of	NNE.	1	7.2	15
Coyote Point	NE.	2	6.4	16
	ENE.	1	3.2	14.5
	E.	5	8.1	14
Average		14	8.5	
Point Pinole	N.	5	11.3	14
	NNE.	1	7.2	11.5
	NE.	2	6.4	11
	ENE.	1	3.2	8.5
	E.	5	8.1	4
Average		14	8.5	
Alameda Creek	WNW.	5	19.3	22
(Area 1)	W.	26	19.3	9
	WSW.	5	14.5	7
	SW.	11	13.7	7
Average		47	17.5	
Alameda Creek	WNW.	5	19.3	22
(Area 2)	W.	26	19.3	9
Average		31	19.3	
Alameda Creek	NW.	11	14.5	27
(Areas 3 and 4)	WNW.	5	19.3	22
	W.	26	19.3	9
	WSW.	5	14.5	7
	SW.	11	13.7	7
	SSW.	1.5	15.3	7
	S.	6	12.9	6
Average		65.5	16.4	
Alameda Creek (Area 5)	SW.	11	13.7	7
Alameda Creek (Area 6)	S.	6	12.9	0.5

Germination tests were made to determine an optium planting period. At 2-week intervals, seed samples were removed from storage and placed in freshwater. The precentage of seeds that germinated was recorded. Seed samples were also placed in solutions of 0, 10, 20, and 30 parts per thousand salinity to determine the best solution for germination.

(2) Field Planting. Both hand and mechanical seeding was done. The application rate for seeding was approximately 100 seeds per square meter. Hand-sown seeds were raked into the substrate and covered with a thin layer of mud to prevent them from floating. Mechanical planting was performed with a hydromulch machine with a nozzle pressure of about 10 kilograms per square centimeter.

b. Sprigs. A *sprig* is a single stem (culm) with associated root and rhizomal material. Clumps of cordgrass were collected in existing natural marshes and separated into individual sprigs. Only culms without inflorescenses, ranging in size from 7 centimeters tall in the spring to 25 centimeters tall in the fall, were used. The sprigs were hand-planted to a depth of 7 to 10 centimeters, depending on the sprig size. A hole was pressed into the substrate, the sprig was placed in the hole, and then the mud was compressed around the sprig.

c. Plugs. A *plug* is a group of stems with attached root and rhizome material which is collected and planted with the sediment mass intact. Tests were conducted on two types of plugs: (a) plugs protected by construction shingles inserted in the mud to act as wave breakers; and (b) bioconstructs with ribbed mussels (*Ischadium demissum*, formerly *Volsella demissus*) imbedded in the rhizome mass.

(1) Plugs With and Without Wave Breakers. Plugs, 15 centimeters square and up to 10 centimeters tall, were collected from dense cordgrass stands. The plugs were selectively dug to obtain a maximum number of culms per unit of surface area. Holes were dug into the mud with a square-tipped spade, deep enough for the planted plugs to be flush with the mud surface. The plugs were then pressed into the holes by hand. To protect each plant, construction shingles, measuring 15 to 25 centimeters wide and 30 centimeters long, were pressed 20 centimeters into the substrate. For very small plugs, two shingles were placed in a "V" formation in front of the plant with the apex facing the wave fronts. Larger plugs were protected by arranging three or four shingles in a staggered pattern across the exposed side of the plant.

(2) Cordgrass Mussel Bioconstructs. Cordgrass plugs with ribbed mussels were obtained from a stand fully exposed to bay wave activity, located approximately 1.5 kilometers north of Alameda Creek. The bioconstructs measured approximately 25 centimeters square and up to 15 centimeters tall. Although the cordgrass was stunted in height, as was typical in stands exposed to strong wave action, it was healthy in terms of density of shoot growth and the lack of noticeable necrosis. The planting procedure was the same as for the plugs without ribbed mussels with three additional steps. The substrate surface was manually

compacted (sealed) around the perimeters of the bioconstructs to protect against wave surges. Then, a wooden dowel 1 meter in length was pressed vertically through the center of each bioconstruct after it was planted (Fig. 4). Each dowel had a "T" top made by forcing it through a slightly undersized hole in the center of a piece of wood. Wooden planking was used to construct walkways in the plots during the planting operation to minimize substrate disturbance.

Figure 4. A cordgrass-ribbed mussel bioconstruct showing top of dowling used to stabilize the transplant.

5. Experimental Design for Field Plantings.

The evaluation of field-planting techniques was conducted in two phases. Phase one focused on determining the relative tolerance of seeds, sprigs, and plugs to wave activity. Phase two focused on developing improved plug-planting techniques for erosion control.

a. Phase One--Comparison of Seeds, Sprigs, and Plugs. San Mateo and Alameda Creek (area 1) were selected for the phase one plantings. The San Mateo site was planted between 14 and 25 July 1976 and plant survival was determined in August and December 1976. Alameda Creek (area 1) was planted in May 1976 and monitored in August and October 1976 and January 1977. The following is a summary of plant materials used at each site.

San Mateo	Alameda Creek (area 1)
Seeds (hand), 23 liters	Seeds (hand), 20 liters
Seeds (hydroseeding), 150 liters	Sprigs, 628
Sprigs, 360	Plugs, 54
Plugs, 108	

Plantings in this phase were not organized into replicate plots and data analysis was strictly subjective.

b. Phase Two--Development of Plug Planting Techniques.

(1) Plugs With and Without Wave Breakers. San Mateo, Point Pinole, and Alameda Creek (area 2) were chosen to test plugs with and without wave breakers. Plot size at each location was 4 by 4 meters; plugs were planted on 1-meter centers, 16 plugs per plot. Schematic drawings of the randomly designated, replicate plots are in Figure 5. All plots were planted in September 1976, and monitored in October 1976, January, April, July and October 1977, and January 1978. Percent survival, stem height, and stem density were determined during each period.

(2) Cordgrass Mussel Bioconstructs. During field monitoring of the wave breaker plots at Alameda Creek, it was noted that several areas of the shoreline were stabilized with ribbed mussels growing in conjunction with California cordgrass (Fig. 6). Five experimental plots (areas 2 to 6) at Alameda Creek were established to test the feasibility of using cordgrass-mussel bioconstructs for erosion control. The five plots which were not true replicates, represent a range of shore conditions. All plots were 5 by 5 meters with 25 cordgrass-mussel bioconstructs planted on 1-meter centers in June 1977. Alameda Creek (area 2) provided a comparison between cordgrass-mussel bioconstructs and plugs with and without wave breakers planted at this site in 1976. No plants from the 1976 plantings remained at Alameda Creek (area 2) at the time of the 1977 planting. Alameda Creek (area 3) was established as a control for the planting method. Cordgrass-mussel bioconstructs were transplanted into a natural cordgrass-mussel community. Alameda Creek (areas 4, 5, and 6) represented three alternative exposures to wave action. A

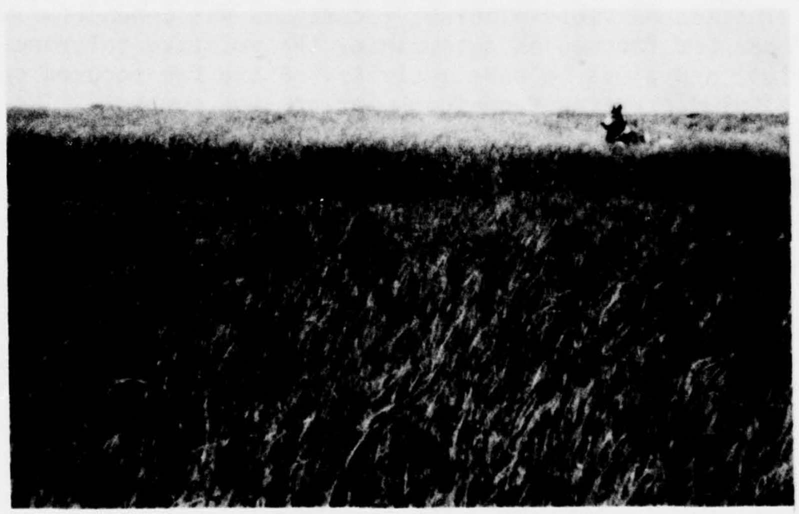

Figure 6. Natural cordgrass-mussel community.

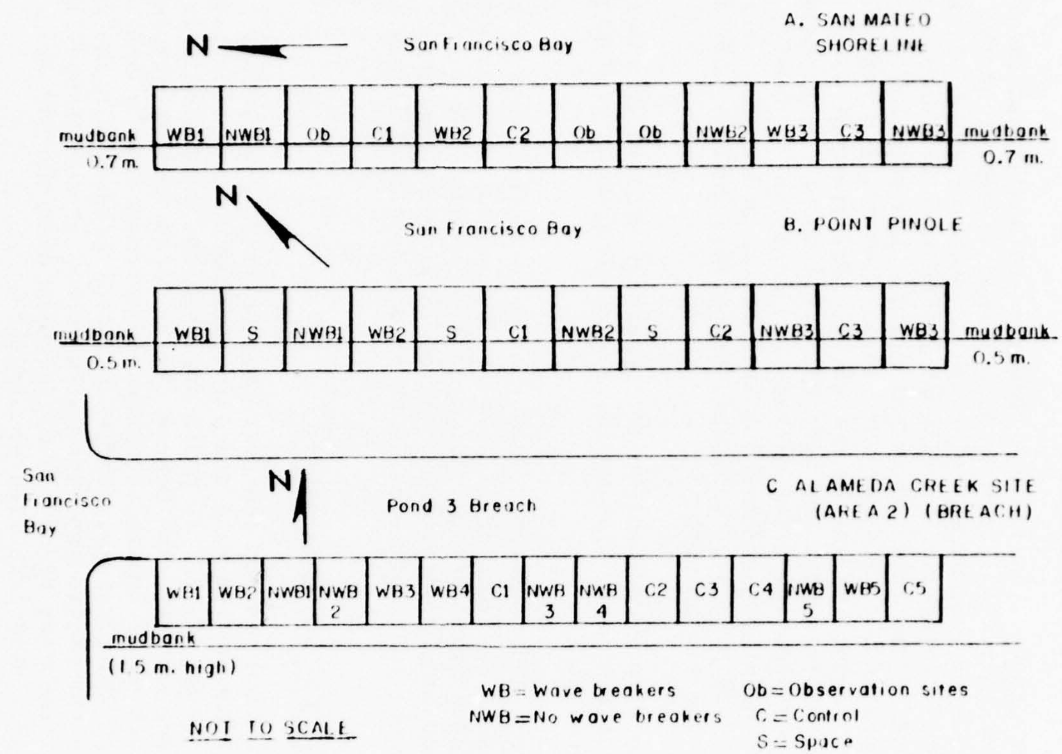

Figure 5. Experimental plot arrangement for Alameda Creek (area 2, breach), San Mateo shoreline, and Point Pinole.

schematic of the plot arrangement is shown in Figure 7. Percent survival, stem height, and stem density were determined in each plot during monitoring periods in December 1977, and February and June 1978.

V. RESULTS

1. Survey of Natural Cordgrass Marshes .

a. General Observations. California cordgrass naturally establishes in the middle to upper intertidal zone by either seed dispersal or the fortuitous introduction of a dislodged plant with root or rhizomal tissue. Individual plants spread laterally by rhizomal growth with new shoots emerging up to 50 centimeters from the parent plant. New shoots grow rapidly and often sprout one to five or more basal shoots which generally emerge within 1.5 centimeters of the parent shoot. Inflorescent (seed head) development begins in August and seed dispersal occurs in November. Most of the inflorescent-bearing culms dieback by January or February. Most of the seed crop undergoes germination in February and March. Vernal growth in established plants also begins during this period. Aerial stems are present during all seasons.

Plants exposed to strong wave action are generally stunted in appearance. This may result from high stem mortality and continuous replacement of lost stems with new shoots.

b. Survey Results. Table 3 summarizes the data obtained from survey of 23 natural marshes in November 1976. The average number of stems per square meter area ranged from 224 to 1,460. Aerial biomass ranged from 367 to 2,030 grams per square meter area for the 23 sites. Mean stem height ranged from 55 to 100 centimeters with a mean height of 79 centimeters.

2. Laboratory Studies on Seed Germination.

Laboratory germination studies indicate that California cordgrass seeds have twice the germination rate and also germinate faster in freshwater than in solutions of 10, 20, 30 parts per thousand saltwater (Fig. 8). Similarly, Mooring, Cooper, and Seneca (1971) noted that freshwater stimulates the germination of smooth cordgrass (*Spartina alterniflora*). It may be assumed that under natural conditions seeds produced in the fall either float in bay water or are deposited with debris in the strand line. Winter rains cause a temporary reduction of salinity near the bay and tributaries and probably stimulate seed germination.

Laboratory studies also show that seed collected in November and stored in 40 parts per thousand saltwater reached peak germination in May (Fig. 9). This "after ripening" has also been observed in studies of smooth cordgrass. A delay in peak germination in natural stands of cordgrass until late winter or early spring, when climatological conditions and salinities are more favorable, is an advantage to plant survival.

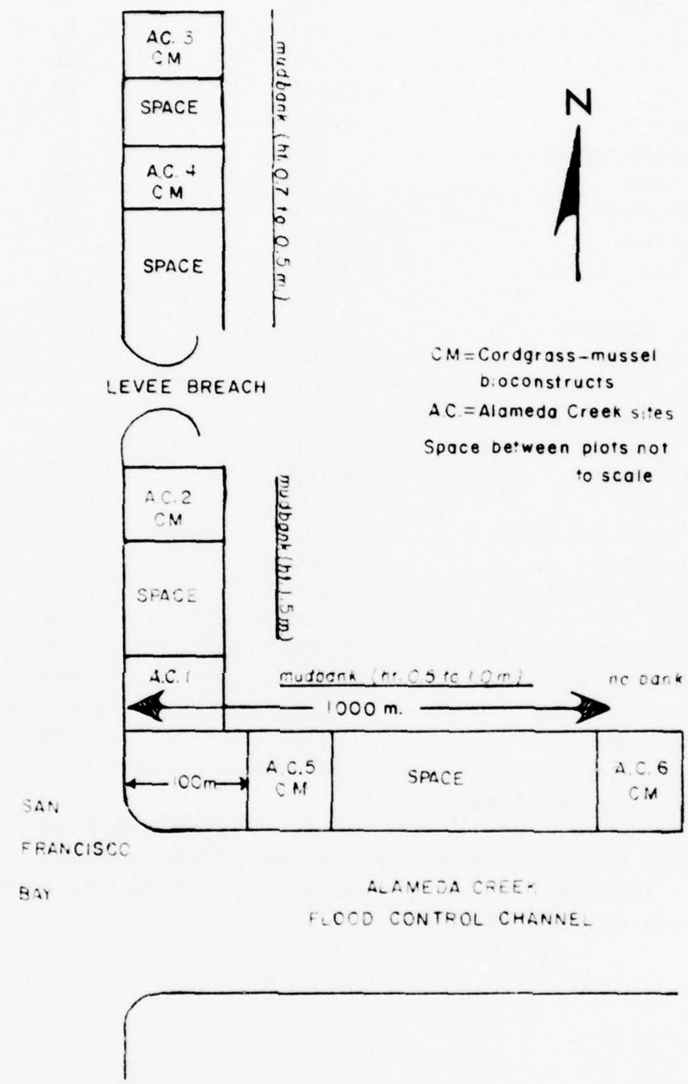

Figure 7. Experimental plot arrangement for Alameda Creek (areas 2 to 6) showing cordgrass-mussel bioconstruct plantings.

Table 3. Measurements of California cordgrass stands in San Francisco Bay.[1]

Site	Aerial biomass[2] (g/m^2)	Mean height of stems (cm)	Mean number[3] of stems/m^2
Alameda Creek	549	55	420
Bay Bridge Toll Plaza	771	65	400
Bolinas Lagoon	1,040	86	285
Burlingame	2,030	82	1,460
China Camp	1,060	92	862
Corte Madera Creek	802	80	958
Coyote Point	1,300	86	526
Creekside Park	1,120	81	403
Drakes Estero	1,040	96	224
Golden Gate Fields	518	71	495
Limatour	367	58	377
Marin Day School	1,100	91	657
Novato Creek	1,050	81	442
Oro Loma	1,160	95	1,170
Palo Alto Audubon Preserve	554	71	495
Petaluma Creek	1,050	74	377
Pinole Creek	1,470	97	737
Pinole Creek (Mouth)	663	69	443
Richardson Bay	632	70	566
San Francisco Airport	1,670	62	765
Seal Slough	1,590	78	614
Shoreline Drive Alameda	1,170	73	960
South Hampton Bay	1,730	100	1,310
Average	1,062	79	650

[1]Four replicates at each site.

[2]Aerial biomass - dry weight of all living and dead plant material more than 2.5 centimeters above the ground surface.

[3]Stems - includes (a) dry, dead stems, (b) living green stems, and (c) emerging, new shoots.

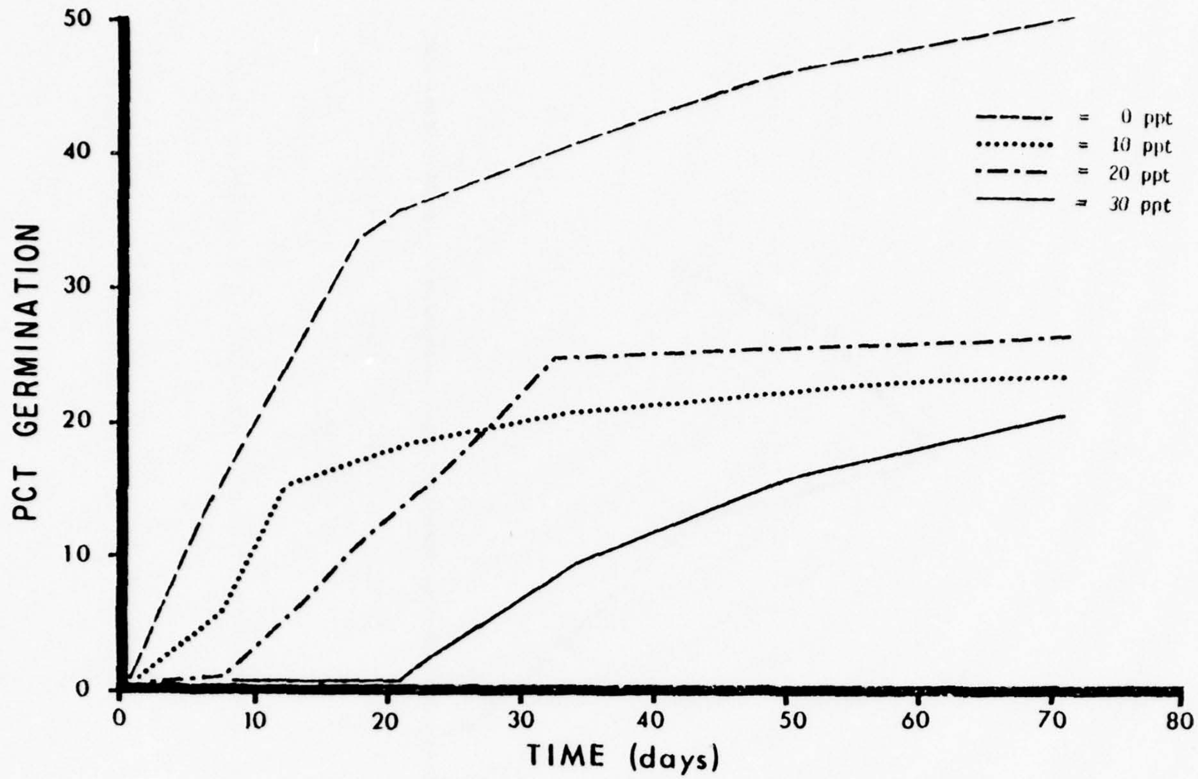

Figure 8. Germination of California cordgrass seed in varying salt concentrations.

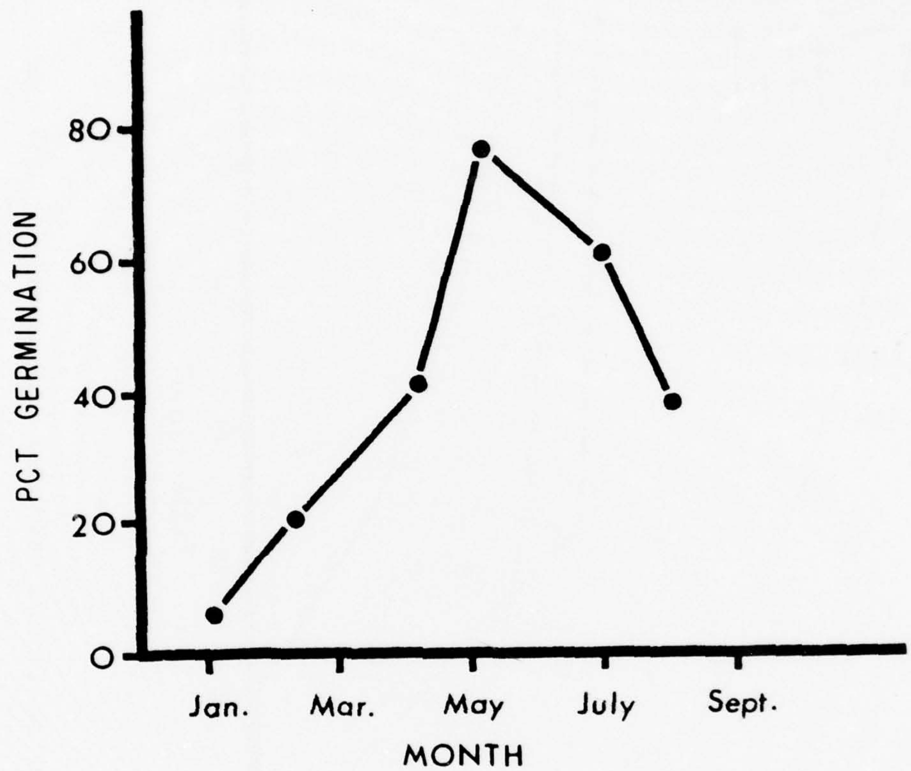

Figure 9. Germination of stored California cordgrass seed.

3. Comparison of Seeds, Sprigs, and Plugs.

A comparison of the success of using seeds, sprigs, and plugs to establish a marsh was made at San Mateo and Alameda Creek (area 1). The San Mateo site is located on the western shore of San Francisco Bay and is not exposed to prevailing winds. The site faces fetches from 14 to 21 kilometers, but winds blow onshore only about 14 percent of the time at an average speed of 8.5 kilometers per hour. The Alameda Creek (area 1) site is exposed to the prevailing westerly winds. Winds blow onshore at this site about 47 percent of the time at an average speed of 17.5 kilometers per hour. Area 1 is also exposed to broader fetch ranges from 11 to 35 kilometers.

A 150- by 15-meter area of the San Mateo site was hydroseeded (seed in water applied by hose from a tank truck) with 150 liters of seed. Inspection of the site immediately after seeding indicated that the process had torn the seed embryos from their hulls. Two days later, the only evidence of seeding was the presence of a drift line of seed debris. Parts of the hydroseeded area were hand-raked and additional areas were hand-seeded and raked. No seed germination was observed using either of these techniques. Hand-seeding attempts at the Alameda Creek (area 1) were also unsuccessful, due probably to exposure to wave action (Table 2).

Sprigs and plugs were planted in front of, and extending up, a 0.2-meter bank at San Mateo in July 1976. One month after planting, only 54 percent of the plugs and 6 percent of the sprigs survived. Greatest mortality occurred on, or immediately beneath, the bank. Five months after planting, no plants were alive.

Sprigs and plugs were planted at the Alameda Creek (area 1) site in May 1976. At some locations of this site there were banks 0.3 meter high. In August, 3 months after planting, only 30 percent of the plugs and 5 percent of the sprigs were alive. Five months after planting, plug and sprig survivals were 13 and 2 percent, respectively Eight months after planting, there were no live plants, reflecting high exposure to waves.

Seed, sprigs, and plugs were not successful in establishing vegetation on the two exposed sites tested. Seeding offers little promise whereas, plugs appear to be more tolerant to wave action than sprigs.

Having determined that plugs are more tolerant to wave action than seeds or sprigs, the 1977 planting focused on improving establishment techniques for plugs.

4. Plugs with Wave Breakers.

As discussed previously, plugs with and without individual shingle-type wave breakers were planted in replicate plots at the Alameda Creek (area 2), San Mateo, and Point Pinole sites. Figure 10 and Table 4 summarize survival and growth of the plugs with and without shingles.

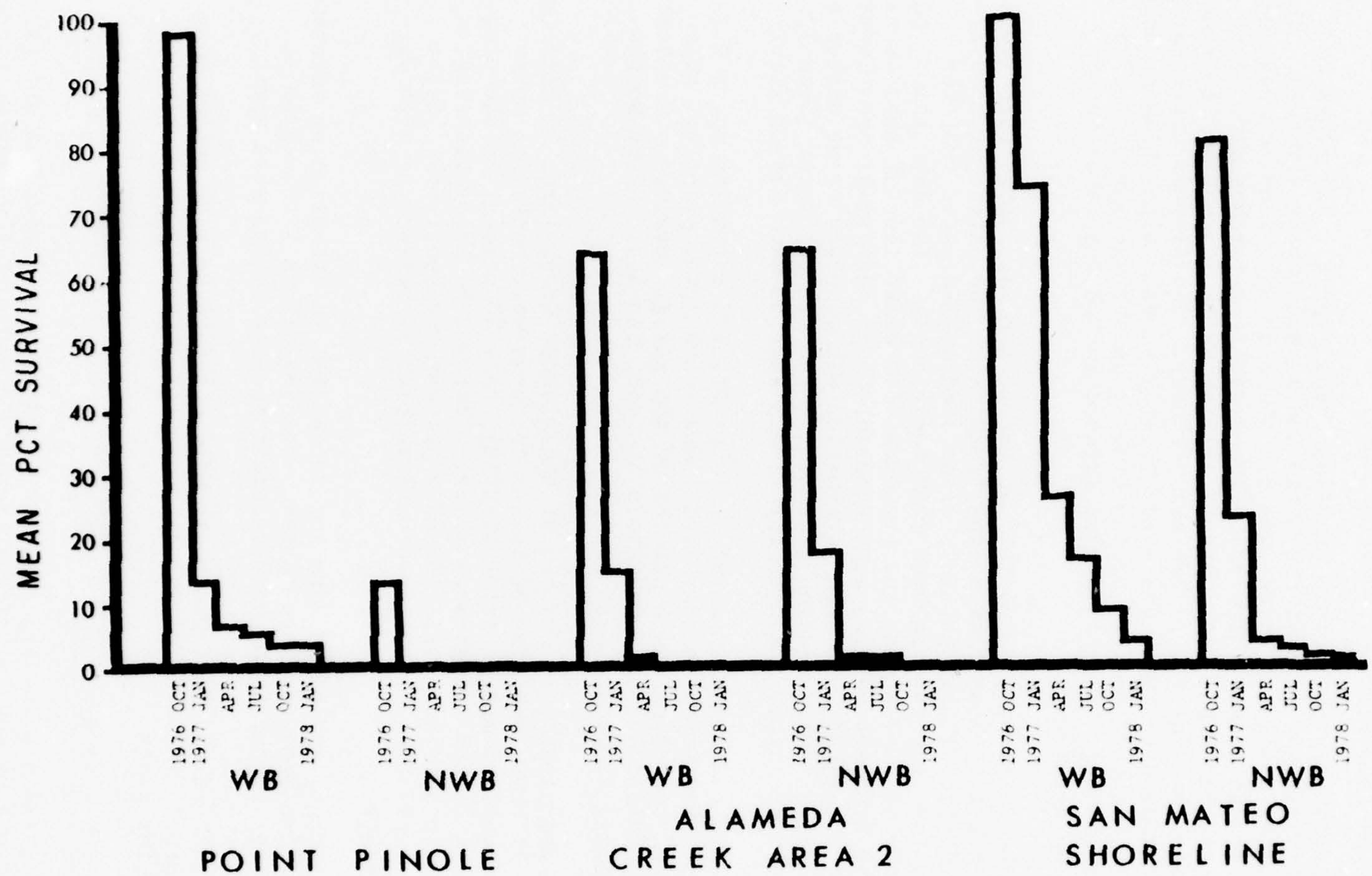

Figure 10. Survival of plugs with wave breakers (WB) and without wave breakers (NWB).

Table 4. Comparison of survival and growth of plugs with and without wave breakers.[1]

Sites	Months after planting															
	2	5	8	11	14	17	5	8	12	14	17	5	8	12	14	17
	Pct survival						Average number of stems/plug (stems/m^2)					Average stem height (cm)				
Point Pinole																
with WB[2]	98	14	7	4	6	4	2.08	1.71	3.48	5.00	3.13	4.5	5.0	3.3	4.0	3.6
without WB	14	1	0	0	0	0	0.25	0	0	0	0	2.5	0	0	0	0
Alameda Creek (Area 2)																
with WB	64	22	3	1	0	0	2.94	0.05	0.18	0	0	3.4	8.0	5.0	0	0
without WB	65	29	2	1	0	0	3.25	0.11	0.03	0	0	5.3	5.0	5.0	0	0
San Mateo																
with WB	100	74	27	17	9	4	22.63	6.92	7.00	2.81	1.38	3.7	6.7	9.3	12.7	2.2
without WB	81	23	4	3	2	1	6.02	0.44	0.38	0.88	0.67	3.0	7.0	8.5	9.5	7.1

[1]Planted September 1976.
[2]WB = Wave breakers.

a. Alameda Creek (Area 2) Plantings. Area 2 is a particularly high-energy site which is subject to both strong tidal currents and wind waves. The site borders on a manmade breach in the South Bay levee system. The breach connects the bay with a 100-acre pond. During high and low tides, the pond is filled and emptied through the breached section. During peak periods, velocities through the breach reach 0.5 to 1.0 meter per second (U.S. Army Engineer District, San Francisco, 1976). In addition, this site is exposed to strong westerly winds which generate waves over a broad fetch, 9 to 22 kilometers. Winds blow onshore at Alameda Creek about 30 percent of the time at an average speed of 19 kilometers per hour. Observations using reference stakes indicate that the 1.7-meter bank at this site erodes several meters per year.

The wave breakers had no effect on plant survival at Alameda Creek (Table 4). The unstable substrate eroded rapidly and the wave breakers were frequently washed into the higher elevated pickleweed and saltgrass zone. In addition, most plants at the Point Pinole and San Mateo sites were planted on relatively level ground, beneath or on a mudbank; plants at the Alameda Creek site were planted on an unstable, steep slope of the mudbank where the plants were easily dislodged by waves.

b. San Mateo Plantings. The San Mateo site is exposed to a fetch similar to Alameda Creek, 14 to 21 kilometers. However, this site faces northeast and is totally sheltered from the prevailing westerly winds. Winds blow onshore only 14 percent of the time at an average speed of 8.3 kilometers per hour.

At the San Mateo site, the beneficial effect of the wave breakers was statistically significant by January 1977. During a 3-month period (November 1976 to January 1977), plant survival in all plots was about 50 percent. During the following 3 months (to April 1977) the apparent difference in survival shown in Table 4 was, however, not statistically significant due to high variability in one plot of each group in which the plants died (student's t-test).

c. Point Pinole Plantings. The Point Pinole site is the most sheltered of the three sites. It faces northeast as does the San Mateo site, but winds generate waves over a fetch of only 4 to 14 kilometers at this site. At the Point Pinole site, the survival was significantly greater in the wave breaker plots after the first month (October 1976; Table 4). The t-test showed the probability of the null hypothesis (PH_o) to be smaller than 0.01. By January 1977, the effect of the wave breakers on plant survival at Point Pinole was not statistically significant ($0.30 < PH_o < 0.50$). Wave activity had reduced plant survival in all plots and the variability of the survival was too great for the t-test to show a significant difference.

Though individual wave breakers improved plug survival, it is evident from these plantings that more formidable wave protection is required to establish plants in these test areas. Earlier estimates (Knutson, 1977) that California cordgrass can be established in areas with fetches up to

16 kilometers seem to be overly optimistic. Plugs failed at the Point Pinole site despite the fact that it was totally sheltered from prevailing winds; it faced a fetch of up to 14 kilometers.

5. Cordgrass-Mussel Bioconstructs.

Plugs harvested from mats of cordgrass in association with ribbed mussels have not been previously tested as a bank stabilization technique. However, studies by Newcombe (1941-1946) at Wachapreague, Virginia, found that smooth cordgrass marshes could be established on bare mud areas by heeling in plugs dug from a climax, mat formation cordgrass mussel community (Fig. 11). Pestrong (1972), in his geological studies of San Francisco Bay, observed that these cordgrass-mussel communities had effectively riprapped many channel banks in the South Bay.

Cordgrass-mussel bioconstructs were planted in June 1977 at Alameda Creek (areas 2-6). Data on the growth and survival of cordgrass-mussel transplants are summarized in Table 5 (Newcombe, 1978).

a. Alameda Creek (Area 2) Plantings. Alameda Creek is the high erosion site, as discussed previously. The area 2 plantings were destroyed by bank erosion by June 1978. Instead of "washing out," as the plugs did in the wave breaker plots, they were undermined by erosion of the surrounding substrate until they were sufficiently exposed for waves to dislodge them. Before the plantings were destroyed, their growth was relatively vigorous. The plugs exhibited extensive rhizomal growth by December 1977 (Table 6). Many rhizomes, some of considerable length, grew from the transplants but they were exposed and destroyed by substrate erosion before developing more than a few shoots. By February 1978 all surviving plugs in this plot were damaged too severely for further rhizomal shoot development.

b. Alameda Creek (Areas 3 and 4) Plantings. Alameda Creek (areas 3 and 4) had the greatest exposure to wind waves of the study areas. Winds blow onshore at these areas about 65 percent of the time with an average speed of 16.4 kilometers per hour over a fetch ranging from 6 to 27 kilometers. At area 3, a well-developed cordgrass-mussel community already existed. Plugs planted in area 3 exhibited 100 percent survival after 1 year. The number of stems decreased, as expected, from December 1977 to February 1978, and then increased again by June 1978. This fluctuation was due to waves associated with winter storms. The changes of shoot height and numbers for the cordgrass-mussel bioconstructs matched those of the surrounding cordgrass so closely that it was difficult to discern the bioconstruct transplants at the site after December 1977. The surrounding cordgrass also made it impossible to determine rhizomal shoot characteristics. The success of transplanting in this plot demonstrated that any initial biological stress incurred by the transplanted cordgrass had no lasting detrimental effect on plant survival and growth.

At area 4, no vegetation existed before planting. Cordgrass-mussel bioconstructs planted in this area had good survival after 1 year, but

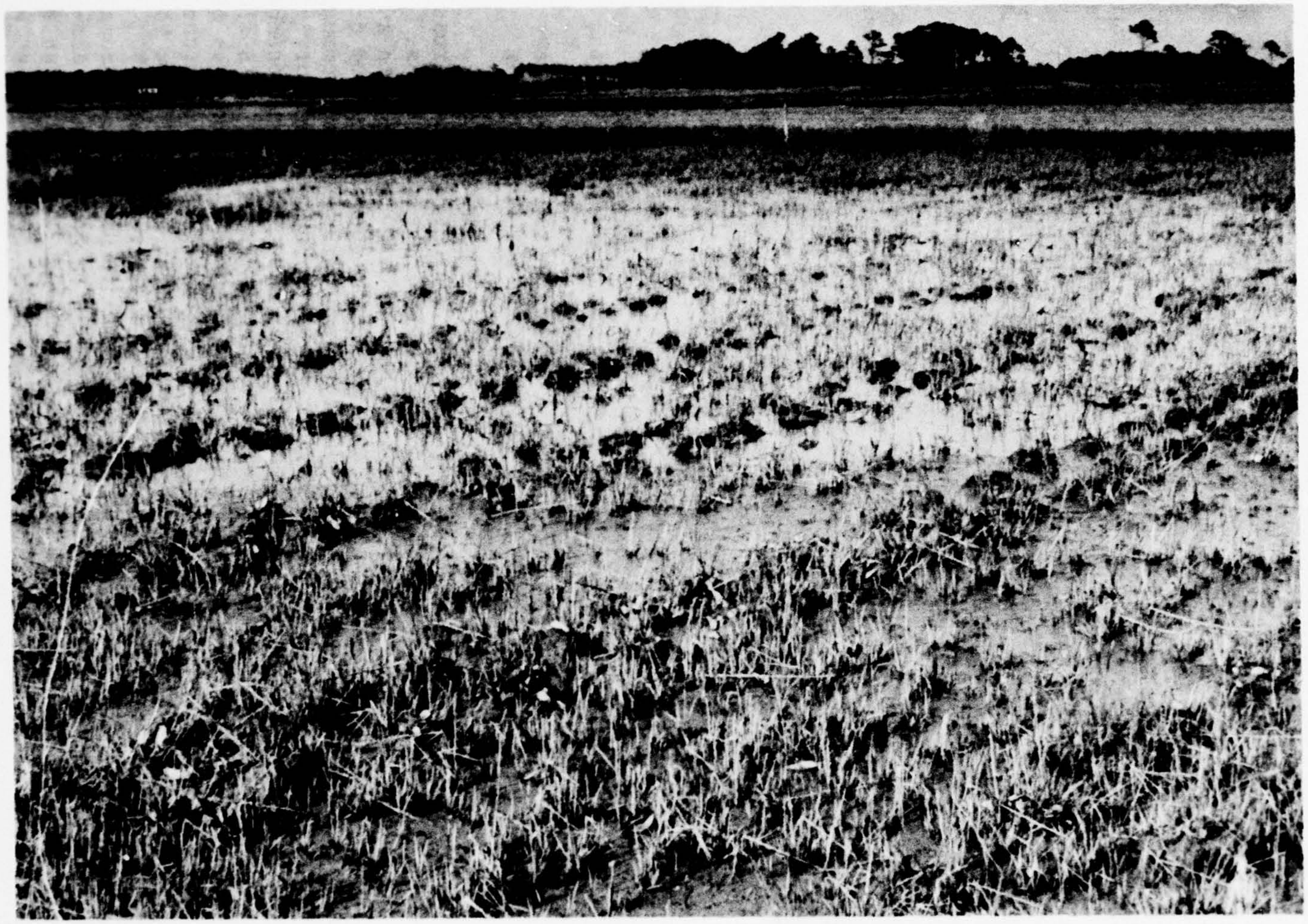

Figure 11. Transplants of smooth cordgrass-ribbed mussel bioconstructs (*Spartina alterniflora* - *Ischadium demissum*) at Wachapreague Marsh, Virginia, 1942 (photo by George M. Moore).

Table 5. Comparison of cordgrass-mussel bioconstruct survival and growth, Alameda Creek (planting date, June 1977).

Alameda Creek Site	Months after planting								
	7(Dec.)	9(Feb.)	13(June)	7(Dec.)	9(Feb.)	13(June)	7(Dec.)	9(Feb.)	13(June)
	Pct survival			Average number of stems/ bioconstructs			Average stem height (cm)		
Areas									
2	84	12	0	85	47	0	6.7	3.0	0
3	100	100	100	105	80	95	4.3	3.9	6.6
4	100	100	96	56	26	11	2.2	2.3	3.1
5	100	100	100	110	128	78	6.3	2.7	4.5
6	100	100	100	120	148	170	9.9	7.5	9.5

Table 6. Comparison of cordgrass-mussel bioconstruct-rhizome development in months after planting, Alameda Creek (areas 2 to 6).

Alameda Creek Site	Months after planting					
	7(Dec.)	9(Feb.)	13(June)	7(Dec.)	9(Feb.)	13(June)
Areas	Mean number of rhizomal shoots per bioconstruct			Length of longest rhizome in plot (cm)		
2	8	0	0	41	0	0
3	--[1]	--[1]	---[1]	--[1]	--[1]	--[1]
4	1	0	2	7	0	2
5	19	35	25	50	39	48
6	21	65	150	37	50	78

[1]Rhizomal growth not measured due to dense cordgrass-mussel communities surrounding plantings.

the overall condition of the plants began to deteriorate immediately and continued to deteriorate through June 1978. The number of stems was about 50 percent of those at area 3 in December 1977 and about 12 percent in June 1978. Rhizomal shoot development was poor as compared to areas 2, 5, and 6 during all monitoring periods (Table 6). The average shoot height decreased to about 50 percent of that in area 3 by December 1977 and remained at that percentage through June 1978. Considering the progressive deterioration of the plants in this area, it is doubtful that this planting will result in long-term stability of the bank. It is evident that new plantings are less tolerant to the destructive forces of waves than are natural cordgrass-mussel communities. Once a stable community has formed and the sediment surface is firmly anchored, individual plants are not subjected to abrasion by sand and shell fragments propelled by waves.

c. Alameda Creek (Area 5) Plantings. Area 5 is partially sheltered from waves generated by the normal westerly to northwesterly winds. The longest fetch in this area is about 7 kilometers. Sediment in this area contained sand and pulverized shell fragments. Cordgrass-mussel bioconstructs planted in this area had 100 percent survival and good plant growth through June 1978. By December 1977 the plants were significantly taller than those in area 3, and the number of stems per bioconstruct was about equal to that in area 3 (Table 5). A mean of 78 stems per bioconstruct was recorded for area 5 in June 1978. This density is comparable to that of the fully developed cordgrass-mussel community at area 3. Although no natural cordgrass-mussel communities were monitored in the 23 marsh sites, it is evident that stem densities are lower when cordgrass grows in association with mussels. Rhizome production and growth of bioconstructs were high in area 5 (Table 6). Based on 13 months of observation, it appears that the cordgrass-mussel bioconstructs will eventually stabilize area 5.

d. Alameda Creek (Area 6) Plantings. Area 6 is located along Alameda Creek and is sheltered from waves with a fetch of less than 0.5 kilometer in any direction. Cordgrass-mussel bioconstructs planted in area 6 exhibited good plant growth within a few weeks. The number of shoots, including rhizomal shoots, continued to increase during the winter period. Shoot height was significantly greater than that in the other areas at all times, although there was some dieback by Februray. The dieback was not a result of the death of inflorescence-bearing culms, as was the case in natural stands, because of inflorescences developed in any of the areas. This area demonstrated cordgrass-mussel growth under optimal conditions. Because of the absence of wave stress, this area was superior in all growth characteristics measured. Stem density in area 6 reached 170 stems per square meter (stems per bioconstruct) and mean height was 9.5 centimeters. As noted earlier, the 23 natural marshes averaged 650 stems per square meter with a mean height of 79 centimeters. The lower density and height in the bioconstruct plots is in part due to their stage of development. However, it appears that even in mature cordgrass-mussel communities stem density remains low in comparison with areas where mussels are not present.

The plantings at the Alameda Creek areas 2 to 6 demonstrated that (a) once established, cordgrass-mussel bioconstructs are highly resistant to wave attack, (b) cordgrass-mussel bioconstructs will survive transplanting, and (c) bioconstructs can be established in an area with a fetch up to 7 kilometers without wave-stilling devices.

VI. SUMMARY AND DISCUSSION

Twenty-three natural intertidal cordgrass marshes in the San Francisco Bay System had an average stem density of 650 per square meter and an average stem height of 79 centimeters. These figures are compared to those reported for natural smooth cordgrass marshes on the east coast. Woodhouse, Seneca, and Broome (1974) reported an average density of 632 stems per square meter and an average height of 72 centimeters for 7 North Carolina marshes.

Laboratory tests show that germination response in California cordgrass is similar to that of smooth cordgrass (Seneca, 1974). California cordgrass seed should be harvested in late October and November and stored in brackish water. Peak germination is reached in March, April, and May, and freshwater is a stimulus to germination.

It is difficult to describe wave environments where vegetative stabilization is effective. There is no single theoretical way to determine the formation of waves generated by winds in relatively shallow water (U.S. Army, Corps of Engineers, Coastal Engineering Research Center, 1977). Fetch, windspeed, wind duration, and water depth are all major determinants of wave climate. In addition, there are many physical and biological variables that must be known to relate wave climate to plant survival. The tidal elevation associated with a particular set of waves and shore topography greatly influence the stress placed upon plantings. Also, the ability of the plant to withstand waves depends on its growth stage, density, and vigor, and the overall width of the planted area.

For this study, fetch was used to qualitatively describe wave climate. The frequency and speed of onshore winds are also important to wave climate analysis (Table 2). In general, the planting sites in this study consisted of a shallow, gradually sloping offshore zone in front of abruptly sloping banks. The success and failure of the California cordgrass plantings exposed to various fetches are summarized in Table 7.

Seeds were the least tolerant to wave attack and had no apparent value in establishing cordgrass for erosion control. Plugs are more wave-resistant than sprigs but were not successfully established on the exposed sites. Sprigs and plugs may possibly be established on eroding banks if adequate wave protection is provided.

Plug transplants harvested from cordgrass-mussel communities are extremely tolerant to wave activity. The ribbed mussels provide a mass of fine byssal threads that attach to the root system of the cordgrass. The compaction of cordgrass roots and dense mussel emplacements held

Table 7. Summary of cordgrass planting results.

Site	Fetch (km)	Plant materials	Effectiveness
Alameda Creek Areas			
1	7 to 22	Seeds	Failure
		Sprigs	Failure
		Plugs	Failure
2	9 to 22	Plugs[1]	Failure
		Cordgrass-mussels	Failure
3	6 to 27	Cordgrass-mussels	Success[2]
4	6 to 27	Cordgrass-mussels	Failure
5	7	Cordgrass-mussels	Success
6	0.5	Seeds[3]	Success
		Plugs[3]	Success
		Cordgrass-mussels	Success
Pond 3	0.5	Sprigs[4]	Success
San Mateo	14 to 21	Seeds	Failure
		Sprigs	Failure
		Plugs[1]	Failure
Point Pinole	4 to 11	Sprigs	Failure
		Plugs[1]	Failure

[1]Plugs with and without individual wave breakers.
[2]Planted in an established cordgrass-mussel mat.
[3]U.S. Army Engineer District, San Francisco, 1976.
[4]Morris and Newcombe, 1978.

together by the byssus threads provides an extremely firm, tightly bound biotic community. Cordgrass-mussel bioconstructs survived (96 percent) during the 13-month observation period at the Alameda Creek (area 4). This was a high-energy area, exposed to prevailing wind over a fetch of 6 to 27 kilometers. However, it is unlikely that this planting will provide long-term stability to the bank. The density of shoots within the bioconstructs declined throughout the observation period. The plants at Alameda Creek (area 5) (7-kilometer fetch) have spread and will probably stabilize the shoreline.

The estimate that California cordgrass can be established by plugs in areas exposed to fetches of about 16 kilometers (Knutson, 1977) seems to be overly optimistic. Plugs failed at Point Pinole despite the fact that it was sheltered from prevailing winds and was exposed to a fetch of only 14 kilometers. The poor survival of all propagules except the cordgrass-mussel transplants suggests that California cordgrass is more difficult to establish on eroding shores than its Atlantic coast counterpart, smooth cordgrass. There is evidence that California cordgrass does not grow and spread with the vigor of smooth cordgrass even when planted in relatively sheltered areas. Plantings by the U.S. Army Engineer District, San Francisco (1974) demonstrated that California cordgrass requires 2 to 3 years to achieve densities comparable to natural marshes in sheltered areas (U.S. Army Engineer District, San Francisco, 1976; Morris and Newcombe, 1977). Researchers have reported total cover in newly planted smooth cordgrass marshes within 1 to 2 years (Woodhouse, Seneca, and Broome, 1974; personal communication, Dr. E.W. Garbisch, *Environmental Concern, Inc.*, St. Michaels, Maryland, 1978). Additional evidence concerning the relative growth of California and smooth cordgrass resulted from laboratory studies conducted in Vicksburg, Mississippi, by Barko and Smart (1976). California cordgrass plants collected from the San Francisco Bay were compared with smooth cordgrass propagules from Louisiana. Plants were grown at a salinity of 24 parts per thousand in sand, silty clay, and clay with an artificially maintained tidal regime. Table 8 shows a comparison of the biomass of the two species after 5 months. Smooth cordgrass growth was nearly twice that of California cordgrass in sand, although growth was more than nine times greater than California cordgrass in silty clay sediments and six times greater in clay sediments.

Despite apparent limitations, California cordgrass is suitable for stabilizing relatively sheltered areas. Planting of sprigs and plugs is likely to be effective only in sheltered coves, lagoons, and the mouths of tributaries unless the plants are protected from waves. However, cordgrass-mussel bioconstructs can be successfully established in areas exposed to fetches of up to about 7 kilometers.

Table 8. Comparison of biomass of smooth and California cordgrasses in laboratory experiments (Barko and Smart, 1976).

Species	Ground levels	Biomass[1] (g/m^2)		
		Sand	Silty clay	clay
Smooth Cordgrass	Above ground	112	1,131	3,056
	Below ground	143	773	1,614
	Totals	255	1,904	4,670
California Cordgrass	Above ground	36	83	390
	Below ground	109	112	355
	Totals	145	195	743

[1]Means of two replicates.

VII. CONCLUSIONS

1. At the end of the 1976 growing season (November), biomass of the aerial parts of 23 natural cordgrass marshes averaged 1,062 grams per square meter. The average density of stems was 650 per square meter and average stem height was 0.79 meter. This is comparable with measurements made in smooth cordgrass marshes in North Carolina.

2. Seeding was not effective in stabilizing an eroding shoreline in San Francisco Bay.

3. Plugs were more tolerant to wave activity than sprigs; however, neither technique will stabilize eroding banks in San Francisco Bay unless the plants are protected from waves.

4. Plugs from cordgrass-mussel communities are the most useful for bank stabilization in the absence of wave protection. Cordgrass-mussel bioconstructs survived and spread during the 1-year study in an area exposed to a 7-kilometer fetch. Further observation is needed to determine if this planting method will lead to long-term bank stability.

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